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FLEXIBLE, COMPACT AND HIGHLY EFFICIENT GRAPHENE-BASED ULTRA-WIDEBAND ANTENNA FOR WEARABLE APPLICATIONS

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Abstract

This article presents the designs and analyses of a co-planar ultra-wideband monopole antenna using graphene as a conductive patch. A graphene-based film (GBF) is used as the radiating conductive layer of the antenna, and a Polydimethylsiloxane (PDMS) is used as a substrate. Since both layers are flexible, they are very suitable for use in wearable technologies. In this study, two basic antenna structures are studied. The design-1 antenna covers 3-11 GHz bandwidth. The simulated antenna efficiency is obtained as 72% at 10 GHz. The antenna size is 30 mm×23.2 mm. The second designed antenna (design-2), stands out with its optimizations, is designed in a smaller size, high gain and wide band features. The size of the second antenna has been reduced to 28 mm×21 mm. Although the conductive graphene layer of the antenna was replaced with a higher conductivity, the substrate material remained the same. In the second antenna design, 3.3-30 GHz ultra-bandwidth and 83% efficiency at 25 GHz have been achieved. In addition, new antenna designs with different conductor and substrate properties on the second antenna design are proposed in this study. The effect of antenna bending was also examined and comparative analyses of the obtained results were made in terms of properties such as efficiency, gain, and radiation pattern. In addition to the use of flexible materials in both the substrate and the conductive layer of the designed antennas, their smaller dimensions, broadband structures and high efficiencies allow these antennas to be used as good candidates in wearable technologies.

Keywords: antenna design, graphene, wearable, ultra-wideband, bending analysis

1. Introduction

The developments in antenna technology in recent years have led to changes in the dimensions, structures, materials and usability of antennas. The increase in the variety of wireless applications in many fields such as security, military, sports, entertainment and space sectors, especially the health sector, increases the demand for these changes. Antennas constitute the most important part of the systems in many applications such as examining the health status of people with body sensors, obtaining situational information of a dangerous fire event from a firefighter, instant communication with a soldier in the field, or taking snapshot information from the vehicle sent to space. Changes in applications began to lead to diversity and changes in the structures of antennas. Antennas have also started to be produced in portable and small sizes in order to be integrated into devices whose sizes and weights have been reduced in order to adapt to mobile technologies. Besides its dimensional changes, it is also possible to place the antennas on different types of materials and even on non-planar surfaces. Thus, wearable antennas have started to take an important place in our lives by attracting great attention in recent years due to their attractive features, light weight, flexibility, low cost and portability, and possibilities to enable detection [1], [2], [3].

Wearable antennas, in practice, refer to antennas designed to be functional not only on clothing but also on wearable devices. These antennas are optimized to perform close to the human body and the structure can be flexible or rigid; they are devices used in many areas from commercial, entertainment, sports, security and health applications. It is offered in various configurations in critical or non-critical situations, as it should work in unsuitable environments and should not restrict the wearer's movements. For example, they have shrunk in size and weighed less to equip mobile technologies; if it is kept close to the human body, the building material has been made flexible and it has become possible to place them on non-planar surfaces [1].

In recent years, textile-based materials have been used to give flexibility to antennas [4]. However, it has been investigated that although these materials provide better flexibility for antennas, they do not work properly in humid and high temperature environments. Therefore, different substrate materials are divided into two classes according to their flexibility or non-flexibility for antenna designs. The first is more rigid structures that are inflexible, such as Duroid, FR4, Rogers; the other is structures consisting of textile-based materials such as fabric, polyester, felt and flexible materials such as paper, PDMS, plastic. The flexible substrate exhibits high efficiency, sufficient gain and stable radiation pat-tern without affecting the bandwidth in case of bending. Polyimide-based films such as paper, PDMS, liquid crystal polymers, polyethylene terephthalate and Kapton are light and flexible substrates with smooth surfaces that can withstand up to high temperatures [5]. Recently, PDMS has been used as a durable and flexible substrate in terms of its mechanical and electrical properties [6] [7] [8].

In the proposed antenna design, PDMS, a silicon-based elastomer, is proposed as a substrate suitable for wearable applications. On the other hand, in wearable applications, the conductive layer used to make the antenna flexible should also be selected from suitable materials. Electro-textile conductive materials are used in flexible antennas. Examples include inflexible materials such as copper, silver, gold, and nickel, as well as flexible materials such as copper fiber, carbon-based or composite graphene, and carbon nanotubes.

Graphene, which is among the flexible and carbon-based materials, offers a promising future for wearable technology with its unique properties and environmentally friendly nature. Graphene is a two-dimensional carbon crystal with very good electrical conductivity allowing high frequency signals [2]. It has been researched that graphene has very surprising and extraordinary properties with its high intrinsic strength and high electrical transport properties [9]. In addition to these, other properties of graphene can be explained as follows [10]: It is transparent, absorbing only 2.7% of the light. Its thermal conductivity is higher than that of known metals. It is flexible, can stretch up to 25% of its own height. It has high mechanical strength, 200 times stronger than steel. It has high electrical conductivity, 103 times more conductive than Si. With its unique band structure, new high-speed devices such as efficient transistors and frequency multipliers are obtained and used in nanoelectronics [11]. These properties of graphene, which can be used in the conductive layer of the antenna, should be expected to directly affect the antenna performance. Graphene may be prepared at certain production stages which is used as a composite with other materials. Thus, changes in some properties such as conductivity and flexibility may occur depending on the production method. With these inspiring properties, the graphene film as a conductive layer is used in the proposed antenna de-sign.

This article presents a very small size wearable antenna with ultra-wide band. Unlike the wearable antennas in the literature, this antenna stands out with some of its features. First of all, graphene, one of the most popular materials of recent years, was used in the conductive layer. The prominent mechanical, electrical and structural properties of graphene have been the main starting point. Secondly, the flexibility of the PDMS used in the base material contributed to the formation of a fully flexible antenna. Third, due to its flexibility, a design that is highly sensitive to bending has been created. Fourth, with its very small size, it can easily adapt to all surfaces, especially the human body. Finally, with its ultra-wide operating frequency, it is suitable for use in many applications. As a result of the designs made, in this article, a unique antenna design designed with graphene conductor, which can be used in wearable applications thanks to its very broadband, compact and flexible structure, is designed. In wearable antenna applications, some studies have been carried out to increase the bandwidth, gain and usage diversity of the antenna used. First of all, the applications where the antenna will be used were determined and suitable geometric structures with small dimensions were created. Then, different materials in the antenna layers were selected and compared. Finally, the performance of the antenna under certain degrees of bending was investigated.

2. Antenna Design

Design strategies and steps are explained in the following sub sections.

2.1. Design-1

The first proposed broadband patch antenna has a size of 30 mm×23.2 mm. The conductive layer of the antenna is chosen as a GBF and has a thickness of 0.25 mm [12]. The GBF used in this design is assumed to be produced based on the graphene production methods as described in details [2]. After a series of production method, the produced graphene film has become very useful and suitable for microwave antenna designs as it exhibits a very high conductivity of 3.3×10^4 S/m, resulting in a very low sheet resistance of about 0.3 Ω/square [2]. A 2 mm thick PDMS with a dielectric constant of 2.65 and a loss tangent of 0.02 is chosen for the substrate of the antenna [8].

The proposed initial antenna geometry is designed to have broadband antenna behavior at the desired center frequency and bandwidth. A geometry of the design-1 antenna is shown in Figure 1 and its optimized dimensions are shown in Table 1.

As can be seen from the Figure 1, the antenna has a co-planar geometry. The gap width (w_5) and the width of the transmission line (w_3) are optimized to achieve 50 Ω characteristic impedance.

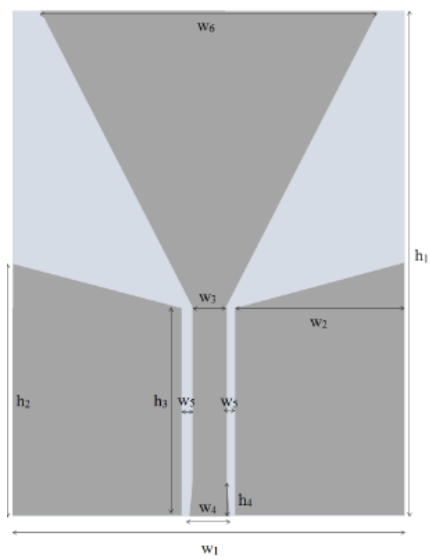


Fig. 1. Proposed design-1 antenna configuration.

Table 1. Dimensions of proposed design-1 antenna.

Parameter	Size (mm)	Parameter	Size (mm)
h_1	30	w_2	10
h_2	15	w_3	2
h_3	12.4	w_4	2.4
h_4	2	w_5	0.4
w_1	23.2	w_6	22

2.2. Design-2

In the second antenna design, which was obtained as a result of optimizing the first design, the antenna size was reduced to 28 mm×21 mm. As in the first design, GBF is used in the conductive layer of the antenna. The graphene used in this new design has a thick-ness of 0.15 mm and a conductivity of 1.94×10^5 S/m [13].

A 2 mm thick PDMS material with a dielectric constant of 2.65 and a loss tangent of 0.02 is chosen for the bottom layer of the antenna [8]. Thanks to the new geometric structure of the antenna shown in Figure-2, the properties of the antenna have been further optimized.

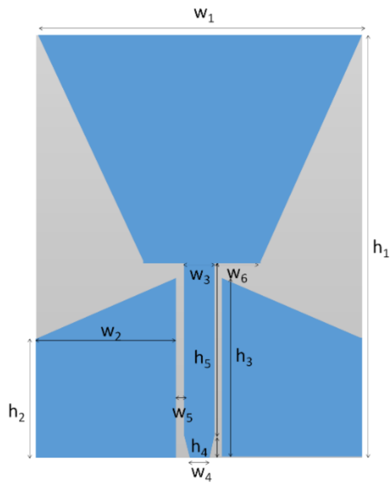


Fig. 2. Proposed design-2 antenna configuration.

The optimized antennas parameters are given in Table 2.

Table 2. Dimensions of design-2 antenna.

Parameter	Size (mm)	Parameter	Size (mm)
h_1	28	w_2	9
h_2	12.3	w_3	2.3
h_3	13.8	w_4	22
h_4	2	w_5	0.8
w_1	21	w_6	2.55

3. Simulation Results of Design-1 and Design-2

The simulation results of the first and second antenna designs are obtained and dis-cussed in this section. The full-wave analyses of the proposed antennas were performed using ANSYS HFSS (version 19.2) based on the finite element method (FEM) to find optimized parameters of the antenna structures in each design step.

3.1. Simulation Results of Design-1

The simulation results are obtained for the design-1 antenna with its dimensions shown in Table 1. Figures 3 shows the real part of the obtained antenna impedance and the unit of impedance is ohm.

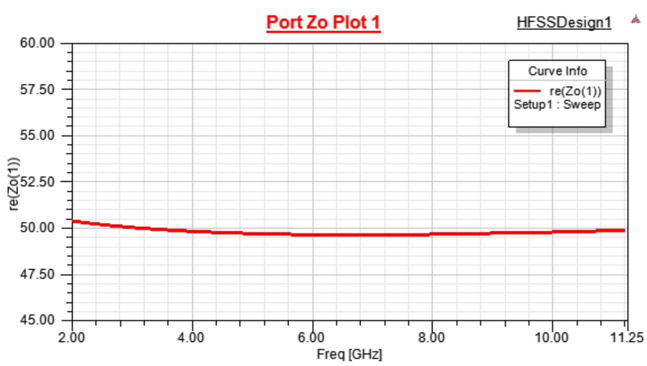


Fig. 3. Real part of the antenna impedance for design-1.

The return loss graph of the designed antenna is given in Figure 3. As can be seen in the figure, the designed antenna has the feature of a broadband antenna operating in the frequency range of 3-11 GHz. The m_1 and m_2 in the S_{11} parameter plot represent the selected points on the figure. These points were chosen because they are the limit points of at least -10 dB. The X and Y points represent the axis values corresponding to these points. The unit of the X point is GHz and the unit of the Y point is dB. This information is valid for all S parameter plots (Figure 4 ,8, 11, 12) in this article.

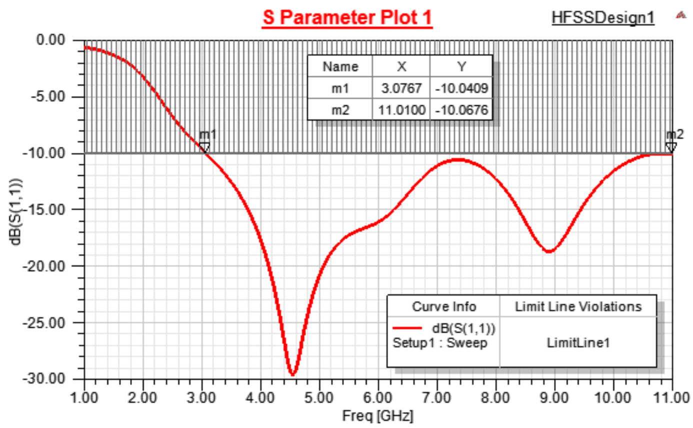
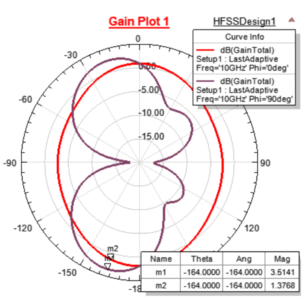
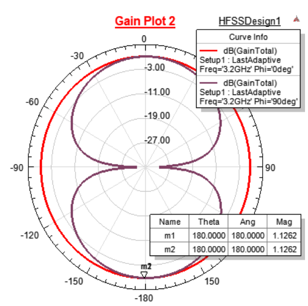


Fig. 4. Simulated return loss (S_{11} parameter) of the proposed antenna for design-1.

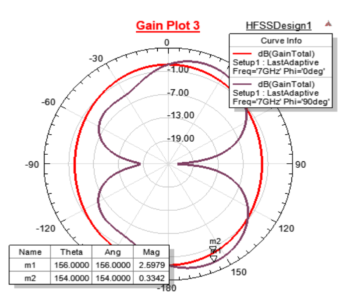
The total gain graphs of the design-1 antenna is analysed at different frequencies and shown in Figure 5. The m1 and m2 in the gain plot represent the selected points on the figure. These points were chosen because they represent the maximum gain values. The mag value on the graph represents the axis values (gain) corresponding to these points and its unit is dB. This information is valid for all gain plots (Figure 5,9,15,19) in this article. The total gain value is 1.12 dB at 3 GHz, 2.59 dB at the center frequency of 7 GHz and 3.51 dB at 10 GHz.



(a)



(b)



(c)

Fig. 5. Simulated total gain on radiation pattern of the proposed design-1 antenna: (a) at 10 GHz (φ=90° and 0°, θ=−164°) (b) at 3 GHz (φ=90° and 0°, θ=180°) (c) at 7 GHz (φ=90° and 0°, θ=154°).

Figure 6 shows the maximum directivity in the frequency range in which the de-sign-1 antenna radiates. It has been observed that the antenna efficiency has its highest value of 72% at 10 GHz.

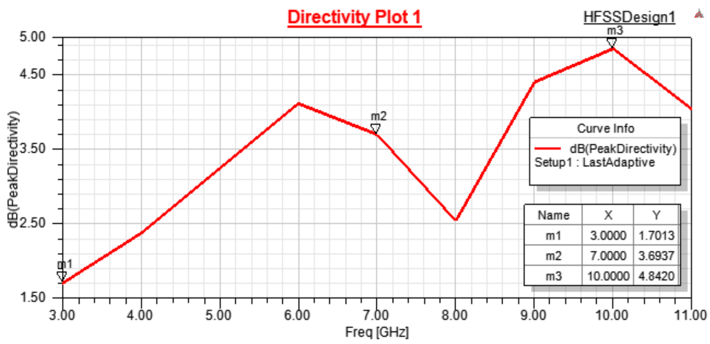


Fig. 6. Simulated maximum directivity for different frequency of the design-1 antenna.

3.2. Simulation Results of Design-2

Simulation results are obtained for the design-2 antenna, the dimensions of which are shown in Table 2. Figure 7 shows the obtained real part of the antenna impedance and the unit of impedance is ohm.

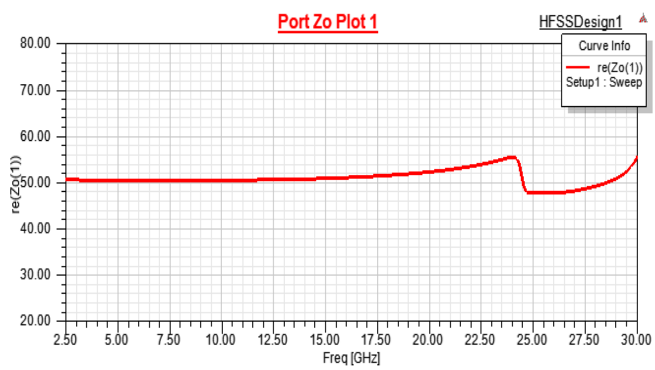


Fig. 7. Real part of the antenna impedance for design-2.

The return loss graph of the antenna in design-2 is given in Figure 8. As seen in the figure, the antenna features a super wideband antenna operating at 3.3-30 GHz frequency range.

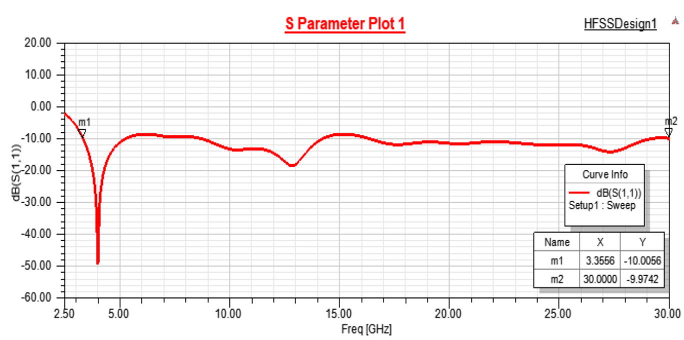
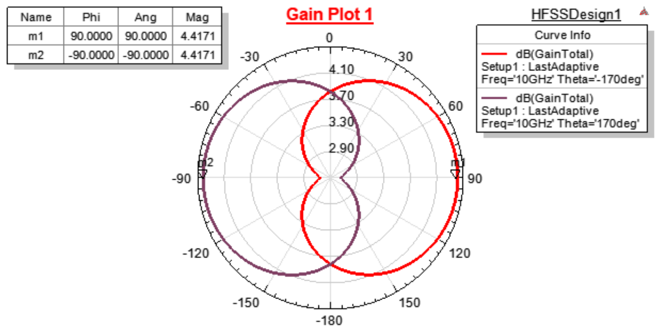
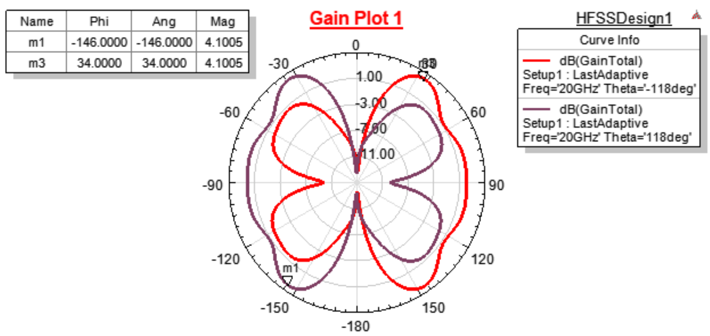


Fig. 8. Simulated return loss (S_{11} parameter) of the proposed antenna for design-2.

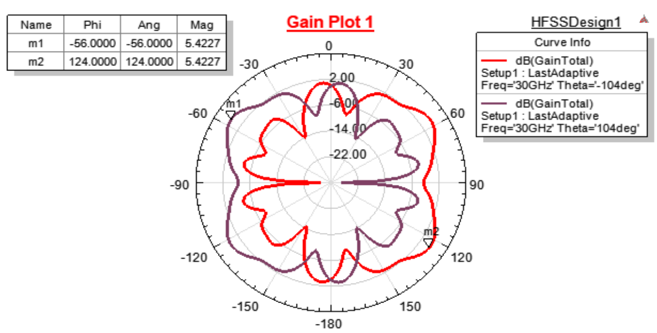
The total gain graphs of the design-2 antenna is analyzed at different frequencies and given in Figure 9. The total gain value is 4.41 dB at 10 GHz, 4.21 dB at center frequency of 20 GHz, 5.4 dB at 30 GHz and 5.7 dB at 25 GHz.



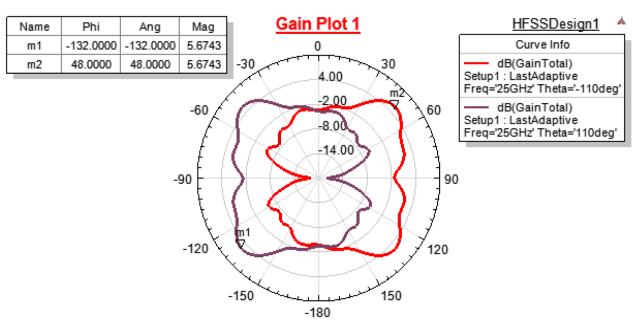
(a)



(b)



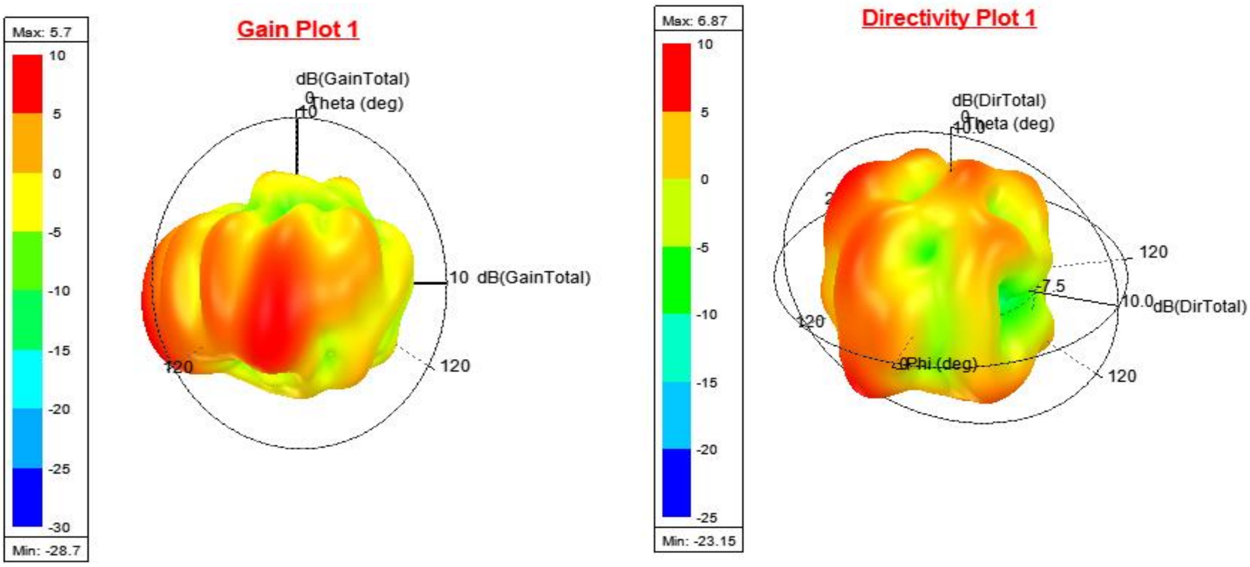
(c)



(d)

Fig. 9. Simulated total gain on radiation pattern of the proposed design-2 antenna: (a) at 10 GHz (φ=-90° and 90°, θ=-170° and 170°) (b) at 20 GHz (φ=-146° and 34°, θ=-118° and 118°) (c) at 30 GHz (φ=-56° and 124°, θ=-104° and 104°) (c) at 30 GHz (φ=-56° and 124°, θ=-104° and 104°) (d) at 25 GHz (φ=-132° and 48°, θ=-110° and 110°).

It is concluded that the maximum antenna efficiency is approximately 83% at 25 GHz operating frequency for design-2 as shown in Figure 10.



(a) (b)

Fig. 10. Simulated polar plot of design-2 antenna (a) maximum gain (b) antenna directivity at 25 GHz.

A comparison of graphene-based antennas with similar characteristics in the literature and the designs proposed in this study is given in Table 3.

Table 3. Graphene-based antenna designs in the literature.

Ref.	Antenna Size (mm)	Frequency (GHz)	Substrate Material	Conductive Material	Conductivity (S/m)	Radiation Efficiency (%)
[4]	47×50	2-8	Cotton fabric and micro-glass fiber	Multi-layer GBF	_	60%
[2]	21.5×29	3.1-10.6	Adhesive tape	GBF	3.3×10^4	80%
[14]	14×22	2.65-10	Rogers TMM4	GBF	1.94×10^5	65%
[15]	24×30	5-13.5	A4 paper	GBF	4.1×10^4	_
[16]	40×40	3.1-10.6	Microwave C-PF-4 foam	Graphite paper	2×10^6	92,3%
[17]	32×48	4.22-10.36	Flexible material	GBF	1.1×10^6	_
[18]	1.57×17.15	8-12	Rogers 5880	GBF	_	94%
Design-1 [12]	30×23.2	3-11	PDMS	GBF	3.3×10^4	72%
Design-2	28×21	3.3-30	PDMS	GBF	1.94×10^5	83%

In order to improve the gain of the antennas in the two designs proposed so far, as well as to obtain a more flexible structure and increase the bandwidth, analyzes were carried out by changing the conductor and substrate materials of the second designed antenna in the following section.

4. New Antenna Designs and Their Performance Comparisons

In this section, the conductor and sub-base materials of the optimized antenna structure (design-2) have been changed to improve antenna performance and the antenna performance of new designs is investigated with the selection of materials suitable for antenna structure. For this purpose, the conductor and substrate materials are changed in four different combinations and obtained results for the new designs are discussed in the following section.

For design-3 and design-4, antenna geometry and substrate properties remained the same. In design-3, the analyzes are repeated using copper instead of graphene conductor; in design-4, the graphene conductor material is used again and the graphene conductivity is changed from 1.94×10^5 S/m [13] to 3.3×10^4 S/m [2].

In the second part of the analyzes conducted in this section, all other features remained the same and only the substrate material of the antenna changed. Two different substrate materials are considered here. The first substrate material used is Kapton Polyimide (relative permeability=3.5 F/m) [5] in design-5. The second substrate material chosen is felt (relative permeability=1.38 F/m) [19] which is a textile product, in design-6.

4.1. Simulation Results for New Antenna Designs

In the first step, the parameters of design-3 and design-4 antennas, which were created by using different conductive materials, were optimized and their performances were investigated: As can be seen from the return loss graphs in Figure 11 and Figure 12, there is not much change in bandwidth and resonance frequency. The unit of the Y1 axis shown in the S_{11} parameter graphs is dB. From the radiation pattern graphs in Figure 15(a) and Figure 15(b), it can be concluded that the antenna gain increases as the conductivity of the material used in the conductive layer of the antenna increases. On the other hand, there is no significant change in the radiation pattern.

In the case of using substrate materials with different properties, the obtained results can be discussed as follows: As can be seen from the return loss graphs in Figure 13 and Figure 14, there have been significant changes in bandwidth and resonance frequencies. The unit of the Y1 axis shown in the graph is dB. In the radiation pattern graphs in Figure 15(c) and Figure 15(d), it has been observed that there is a change in the antenna gain depending on the substrate material change and there are also changes in the radiation patterns.

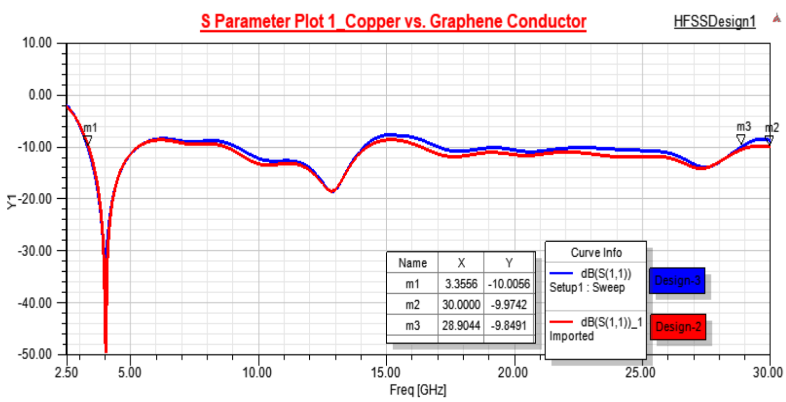


Fig. 11. S_{11} parameter comparison graph for design-2 and design-3.

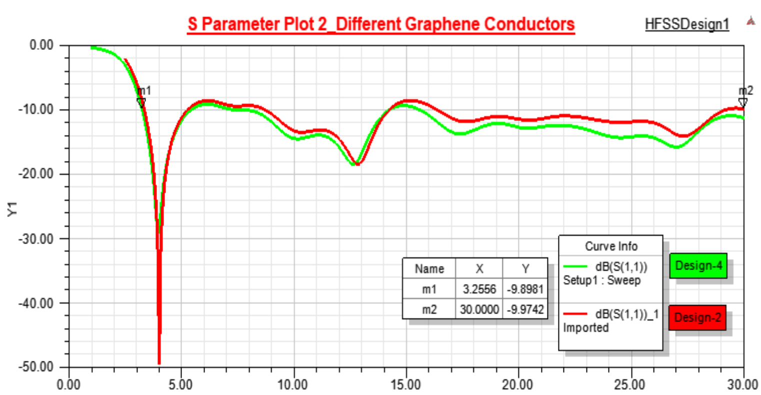


Fig. 12. S_{11} parameter comparison graph for design-2 and design-4.

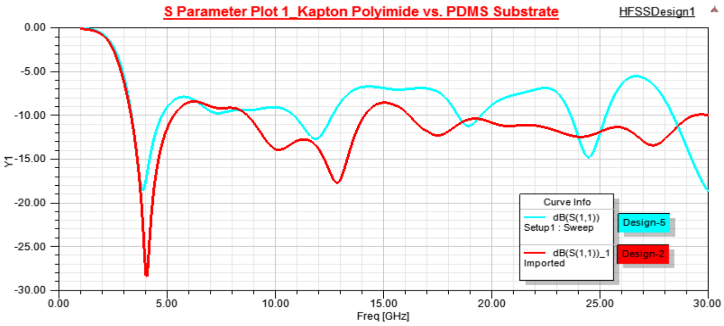


Fig. 13. S_{11} parameter comparison graph for design-2 and design-5.

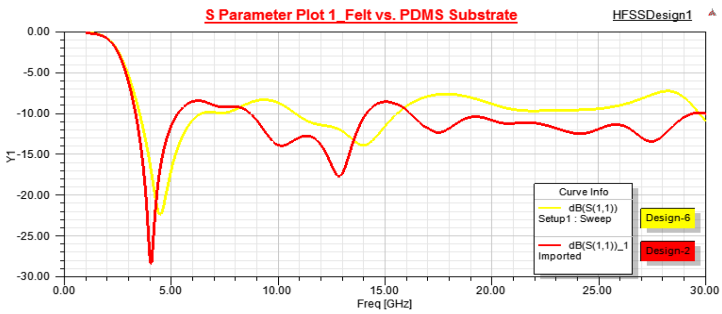
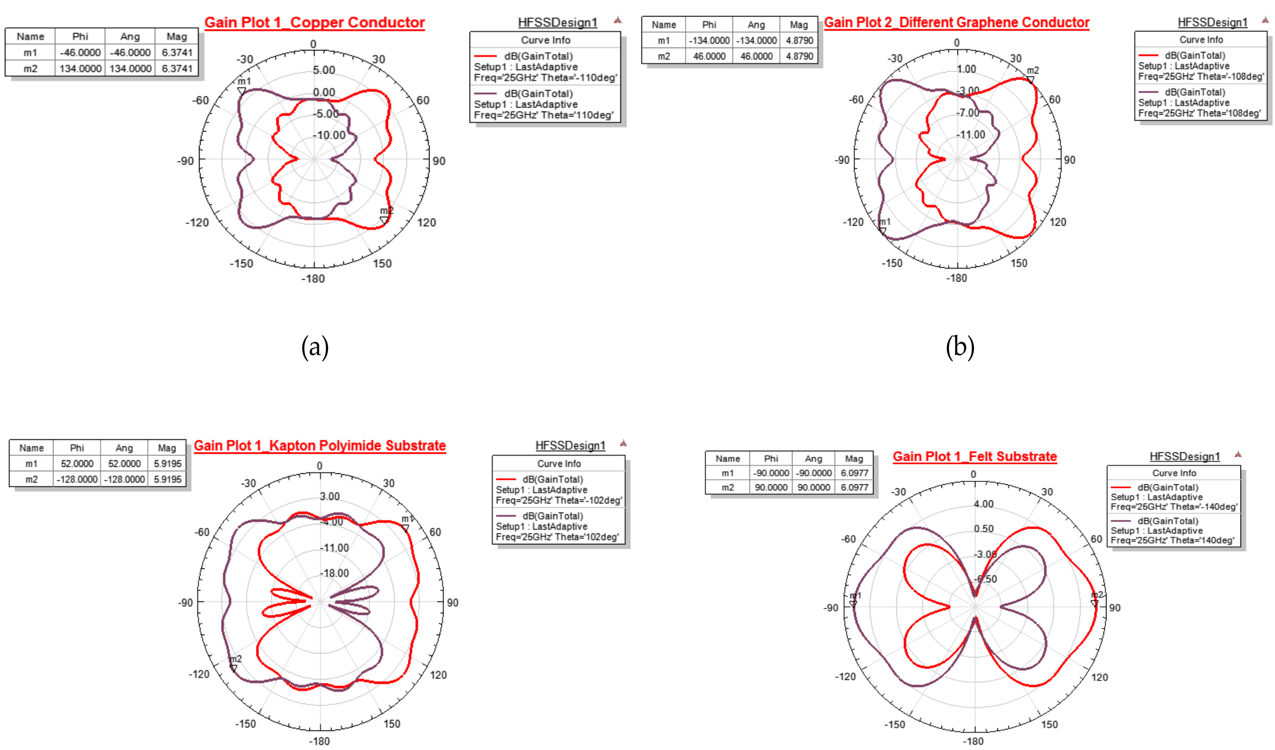


Fig. 14. S_{11} parameter comparison graph for design-2 and design-6.



(c) (d)

Fig. 15. Radiation pattern graph of total antenna gain at 25 GHz (a)using copper as a conductor material (b)using different graphene as a conductor material (c)using Kapton Polyimide as a substrate material (d)using felt as a substrate material.

There are basically two different antenna designs (design-1 and design-2) in the article. Other designs (design-3, design-4, design-5) have been diversified with some changes (substrate and base material changes) made in design-2 antenna. The performances of antenna design with a different structure, together with the performance of the second original antenna, are given in Table 4.

Table 4. Comparison of the designed antennas.

Design Name	Substrate Material	Relative Permeability (F/m)	Conductor Material	Conductivity (S/m)	Bandwidth (GHz)	Antenna Gain (dB)	Antenna Radiation Efficiency (%)
Design-2	PDMS	2.65	Graphene	1.94×10^5	26.7	5.7	83%
Design-3	PDMS	2.65	Copper	5.80×10^7	25.6	6.4	84%
Design-4	PDMS	2.65	Graphene	3.3×10^4	26.75	4.9	62%
Design-5	Kapton Polyimide	3.5	Graphene	1.94×10^5	7	5.9	89%

According to the analysis results given, it has been seen that the use of materials with smaller loss tangent and relative permeability at the bottom of the antenna increases the antenna gain and efficiency. In addition, the use of graphene material with a high conductivity value or the use of copper instead of graphene results in an increase on both the gain and the efficiency. In design-3 and design-5, which have higher radiation efficiency, there were narrowing in the bandwidth. The efficiency of design-3, in which copper is used as a conductive material, is the highest among them. However, this design is not recommended for wearable applications since copper does not have flexibility. The efficiency of design-5, in which Kapton Polyimide is used as the substrate material, is higher than the proposed design-2 antenna. However, since PDMS has great advantages in terms of flexibility, the preferable antenna structure proposed in this article has been determined as design-2.

5. The Bending Performance of the Proposed Antenna

Bending analysis is very important in terms of antenna performance in wearable applications. Therefore, in this section, antenna performance is analyzed in case of bending at certain degrees based on design-2. Figure 16 illustrates the designed antenna bending 30^0 around the y-axis.

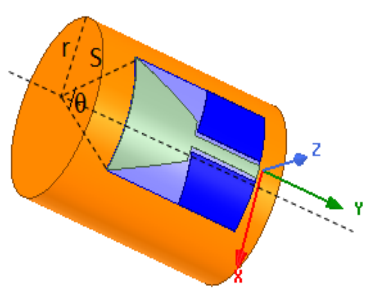


Fig. 16. Image of 30^0 antenna bends for design-2.

The relationship between the bending radius of the antenna and the arc length is shown in the following equation (1) [20]:

$$S = \theta . r \tag{1}$$

S is the bent arc length of the antenna and its unit is meter. θ is measure of the central angle in radians. r is the radius of the cylindrical surface considered as a cylindrical base model for the antenna and its unit is meter. The formula in (1) has been applied to analyze the bending state of the design-2 antenna. For all theta values, the dimension of the S value perpendicular to the bending axis of the antenna (21 mm) is taken.

In this case, the r radius corresponding to the 20^0, 30^0 and 50^0 angles that see the same arc S are calculated according to the equation 1. Different simulations are made by adjusting the radius of the cylinder, which is 61.76 mm for 20^0, 41.17 mm for 30^0 and 24.70 mm for 50^0. The graph in Figure 17 shows the comparison of the bending antenna at different angles. The unit of the Y1 axis shown in the graph is dB.

This can cause the digital machines to malfunction at high exposure and also impact people's health [5-6].

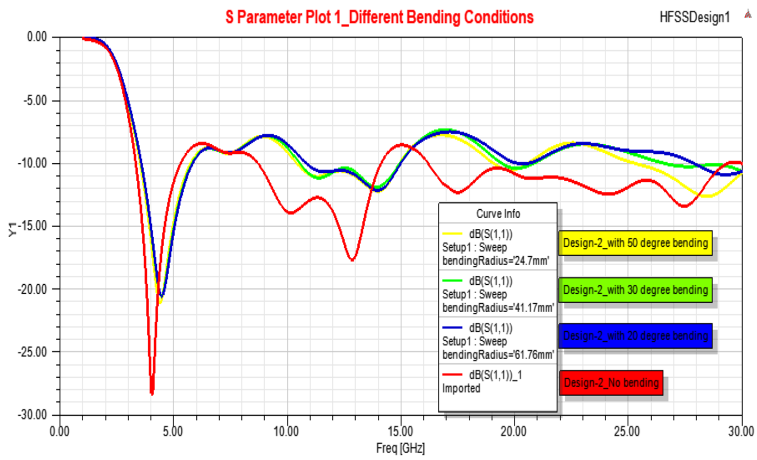


Fig. 17. S_{11} parameter graph at different bending angles of the antenna at 25 GHz for design-2.

The radiation pattern graph of the total gain of the antenna at 30^0 bends is given in Figure 18.

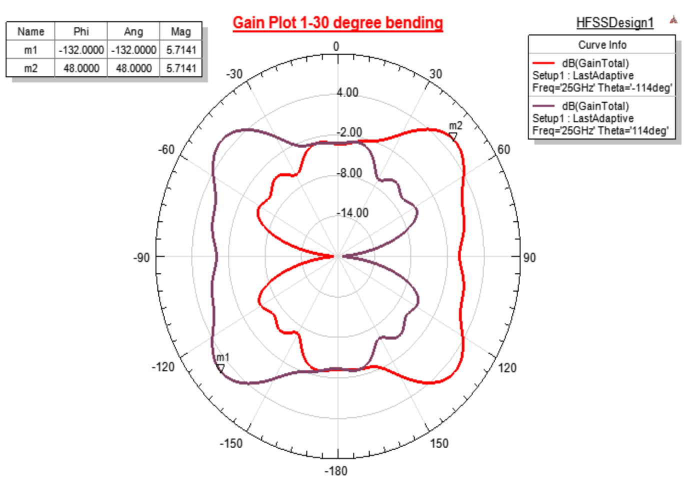


Fig. 18. Radiation pattern plot of total antenna gain at 30^0 antenna bends at 25 GHz for design-7.

As can be seen from the graphs in Figures 17 and 18, there is a slight upward shift in the resonant frequency when the antenna 30^0 is bent. There is no change in antenna gain and bandwidth due to limited antenna deformation between specified angles.

Antenna bending comparison results between the proposed antenna and the similar antennas in the literature are given in Table 5.

Table 5. Bending analysis of antennas in the literature.

Ref.	Antenna Size (mm)	Operating Frequency (GHz)	Substrate Material	Radiation Efficiency (%) or Antenna Gain (dBi/dB)	Antenna Performance in Bending Condition
[21]	55×55	2.45 & 5	Electromagnetic tape	3 dB	There is no significant change in beam width or gain of the antenna.
[22]	20×20	2.4 & 5.2	Textile fabric	2.4 GHz: 3.5 dB 5.2 GHz: 6.6 dB	The operating frequency of the antenna moved upwards at smaller radius.
[23]	37.5×23	2.5-4.6	Fabric	2.5 GHz: -0.42 dBi 4.6 GHz: -3.1 dBi	(Bending radius=50 mm) Bandwidth slightly decreased in the transverse bending of the antenna; maximum gain and radiation pattern remained approximately the same. Antenna gain slightly decreased in longitudinal bending of the antenna and radiation patterns changed slightly.
[24]	30×35	2.93-10.3	Polyamide	3.5 GHz: (No bending): 2.5 dB/ (Bending radius=27 mm): 2.5 dB 5.2 GHz: (No bending): 3.5 dB/ (Bending radius=27 mm): 3.8 dB	When the antenna is bent, the bandwidth and performance remained approximately the same; max gain slightly increased.
[25]	30×40	3-16	Fabric (Agilent 85070E)	2-4 dBi and 80%	The performance of the antenna is not affected.
[26]	11×12	26-40	Rogers ULTRALAM 3850 LCP	35 GHz: 11.35 dBi	Bandwidth and resonant frequency are preserved in folded/twisted structures.
[15]	40×40	3.1-10.6	Microwave C-foam PF-4 foam	92,3%	The operating frequency of the antenna shifts slightly.
Proposed Design	28×21	3.3-30	PDMS	5.7 dB	While there is no change in antenna gain, its efficiency decreased. The return loss graph has shifted from -10 dB to 1-2 dB above.

6. Conclusions

In this article, two separate antenna designs based on high efficiency graphene are examined. The proposed antennas (design-2) have a relatively small co-planar structure and consist of flexible layers that enable the system to be used in wearable applications. This special geometric design-2 proposed is a customized and optimized design according to the requirements of the study, considering the general geometries in the references in Table 5. The design-1 antenna operates in the 3-11 GHz frequency band. The simulation results show that for design-1, the antenna efficiency is 72% in the investigated bandwidth and the antenna gain is around 3.5 dB at 10 GHz. The design-2 antenna, which is also taken as a basis in the analysis, operates in the frequency band of 3.3-30 GHz and an impedance bandwidth of approximately 27 GHz. The simulation results show that the efficiency of the second antenna is 83% and the antenna gain is around 5.7 dB at 25 GHz. According to the bending analysis of the design-2 antenna, it has been observed that the antenna can operate up to about 50^0 without major changes in performance.

Thanks to its small and flexible structure and wide bandwidth, the design-2 antenna, whose features have been improved with optimizations, has a wide application area that requires wearable and operates at different frequencies such as health, military, security, K band applications, Wi-Fi and 5G communication systems. Future works can be considered as follows: designing antennas by using other graphene materials with different properties, making improvements in antenna performance (increasing bandwidth and antenna gain and efficiency), reducing the size of the antenna, adapting the array antenna structure with increased gain, and SAR analysis of the antenna placed in certain parts of the body.

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